

Review

# Life Cycle Assessment of Ocean Energy Technologies: A Systematic Review

María Guadalupe Paredes <sup>1,2</sup>, Alejandro Padilla-Rivera <sup>1,3</sup>  and Leonor Patricia Güereca <sup>1,\*</sup> 

<sup>1</sup> Engineering Institute, Universidad Nacional Autónoma de México, Av. Universidad 3000, Mexico City C.P. 04510, Mexico

<sup>2</sup> Industrial Design Department, Universidad de Monterrey, San Pedro Garza García, Nuevo León C.P. 66238, Mexico

<sup>3</sup> CIRAI, Polytechnique Montréal, Mathematical and Industrial Engineering Department, succ. Centre-Ville, Montréal, QC H3C 3A7 C.P. 6079, Canada

\* Correspondence: LGuerecaH@iingen.unam.mx; Tel.: +52-(55)-5623-3600; Fax: +52-(55)-5623-3602

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**Abstract:** The increase of greenhouse gases (GHG) generated by the burning of fossil fuels has been recognized as one of the main causes of climate change (CC). Different countries of the world have developed new policies on national energy security directed to the use of renewable energies mainly, ocean energy being one of them. The implementation of ocean energy is increasing worldwide. However, the use of these technologies is not exempt from the generation of potential environmental impacts throughout their life cycle. In this context, life cycle assessment (LCA) is a holistic approach used to evaluate the environmental impacts of a product or system throughout its entire life cycle. LCA studies need to be conducted to foster the development of ocean energy technologies (OET) in sustainable management. In this paper, a systematic review was conducted and 18 LCA studies of OET were analyzed. Most of the LCA studies are focused on wave and tidal energy. CC is the most relevant impact category evaluated, which is generated mostly by raw material extraction, manufacturing stage and shipping operations. Finally, the critical stages of the systems evaluated were identified, together with, the opportunity areas to promote an environmental management for ocean energy developers.

**Keywords:** environmental impacts; life cycle assessment; ocean energy; renewable energy; LCA of ocean energy; review of ocean energy; environmental impacts of ocean energy

## 1. Introduction

Nowadays, energy production is mainly based in fossil fuels accounting for an 81.1% of total power generation, contributing 33,481 million tons of carbon dioxide (CO<sub>2</sub>) emissions in 2015 [1]. Nevertheless, fossil fuel reserves are limited, and their use contributes significantly to climate change (CC) due to the emission of greenhouse gases (GHG) [2]. The Intergovernmental Panel on Climate Change (IPCC) states that fossil fuel greenhouse gas emission is the major cause of global warming concern [3]. One of the greatest challenges of this century is to find an alternative energy source to fossil fuels; it should be low cost, ecologically friendly, socially acceptable and highly available for current demand [4]. Therefore, it is important to establish priorities to accelerate cost reduction and market uptake of key low-carbon technologies to improve the environmental impact of energy generation in the world [5]. This type of technology has been directed to the use of renewable energies to minimize potential environmental threat [6,7]. This kind of energy is reliable, usable and environmentally friendly for power generation in a sustainable and decentralized way to provide the electricity supply

at medium and small scale [7]. Overall, it is estimated that renewable energy accounted for 26% of the world's energy generation in 2018 [8].

Among the main renewable energies that have presented growth in their research and development is ocean energy [9]. The world's oceans and seas are an abundant source of diverse forms of renewable energy and comprise a group of low carbon technologies that could play a significant role in the transition of the power sector in the world, contributing to energy security of the countries located close to the sea as well as to the GHG emissions reduction [10]. One of the main advantages of ocean energy compared to other renewable energy sources is its abundance and wide availability [7]. The ocean energy system covers all forms of oceanic renewable resources and can be divided into six types of different origin and characteristics: Waves and tidal energy, marine currents, thermal and saline gradient, and offshore wind [7,11,12]. According with Liu et al. [13], it is estimated that global resources of energy from the ocean are over 30,000 TWh/year, theoretically. However, different surveys have been carried out to evaluate their feasibility and efficiency of these energy technologies, as well as economic, social and environmental issues [7]. Currently, the European Commission has invested in ocean energy research, 45% of the funds being directed to technology development wave energy, 23% to technology development tidal energy, 17% to environmental research and the remaining 15% for other aspects [14,15]. Europe maintains a leadership position in the research and development (R & D) of the ocean energy sector [10]. On the other hand, USA during the last decade has been supporting the ocean energy sector with R & D funding. In Latin America, Chile has very high levels for implementation and deployment with adequate financing strategies; it could be a future leader in regards to the ocean energy system [16].

The development and application of ocean energy systems are limited, and the knowledge about environmental impacts generated by these technologies are too [9]. Nevertheless, the use of these systems is not exempt from the environmental impact's generation throughout their life cycle, including the stages of construction and decommissioning [17].

Direct and indirect environmental impacts due to materials and energy required over its useful life as well as alteration of biodiversity, noise, habitat change and biological pollution can be generated [18,19]. However, limited knowledge contributes to the uncertainty about the potential impacts and their probable magnitude. Based on the latter, life cycle assessment (LCA) is a methodology designed to account for the environmental impacts of a technology over their whole life cycle. In this way, LCA becomes a tool that helps to identify the most critical stages of the life cycle of a system to obtain environmental improvements, in addition, to compare the environmental impacts of systems or technologies that have an equivalent function or performance, allowing decision-makers to select the systems with lower environmental impact [20,21].

In this context, this paper aims to compile and discuss the state of the art LCA practices on ocean energy technologies (OET). The bibliographic review involves the following goals: To gather the relevant studies of LCA on ocean energy; to recognize the different ocean energy types with most advanced scientific and technological progress; to identify the main life cycle stages of OET with the greatest environmental impact; to identify life cycle environmental impacts per type of energy conversion technology and to evaluate improvement opportunities to reduce the potential environmental effects of ocean energy systems. The paper is structured as follows: Section 2 briefly describes some of the main ocean energy technologies. Section 3 provides a detailed review methodology in the present review. Section 4 presents the overview of LCA on OET, including life cycle inventory, life cycle impact assessment, life cycle carbon emissions, carbon and energy payback. Section 5 comprise a general discussion of ocean energy LCAs. The study ends with conclusions (Section 6).

## 2. Description of the Main Ocean Energy Technologies

The world's oceans and seas are an abundant source of various forms of renewable energy. Compared with the other renewable energy sources, the potential for harnessing energy from the

ocean is diverse. Wave, tidal, thermal and gradient salinity energies have been the most research and development technologies worldwide [22,23].

### 2.1. Wave Energy Technology

This is the energy produced by the movement of the waves which is generated by the action of the wind on the sea surface. This type of energy has the advantage of being available throughout the ocean at very low cost and has high energy spatial concentration compared to other renewable energies [7]. There are several wave energy converters (WEC) and these can be classified according to several criteria, among them: Location, devices sizes and orientation, energy capture, energy use, and installation site [15]. Many countries operate WEC devices, including oscillating buoys, floating ducks, snakes, flaps, and enclosed chambers [24]. A fundamental component in these devices is the power takeoff (PTO) system; the mechanism which converts the wave energy into electricity [25]. The power generation capacities of WEC may vary from 10 to 150 kW [15].

### 2.2. Tidal Energy Technology

This is potential energy associated with the periodic rise and fall of the water level (high tide and low tide). The tides are periodic fluctuations in the level of the oceans, due to the gravitational and centrifugal forces between the earth, moon and sun. One of the key advantages of tidal power is its predictability [26,27]. Commonly, the tidal energy technologies function by the movement of tides via a bladed propeller mounted on a hub, with a rotor connecting it to a gearbox, which turns a generator in order to produce electricity [28]. Tidal energy converters (TEC) have been classified in their technical concepts and operation of devices. Based on the device type, including: A horizontal axis with a parallel and perpendicular axis, vertical axis and oscillating hydrofoil, as well as others.

### 2.3. Thermal Gradient Ocean

This is a system that makes use of the temperature difference in the ocean [29]. This energy allows the conversion of the temperature gradient between the surface and the ocean deeps into useful energy. To achieve acceptable performance, it is necessary to have a minimum gradient of 20 °C, which is reached at a depth of 1000 m, using the solar heat stored in warm surface waters to drive hydraulic or vapor turbines [30]. One of the main disadvantages of these systems is their high installation costs. There are mainly three types of technologies for the thermal gradient ocean system, commonly known as ocean thermal energy conversion (OTEC): Close cycle, open cycle and hybrid cycle [15]. The benefits derived from thermal gradient ocean facilities include the potable water production and the use of cold water for aquaculture, refrigeration and air conditioning of seawater [31].

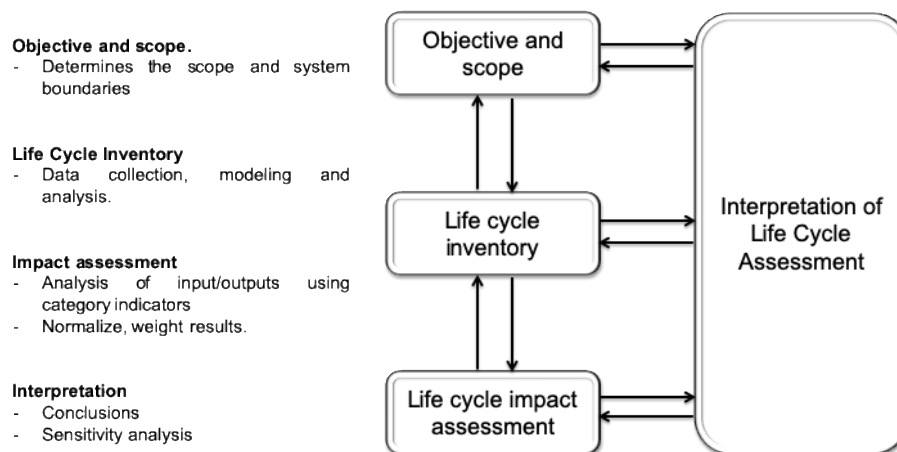
### 2.4. Salinity Gradient Ocean

This is the energy generated from the mixing water of different salinities, commonly; fresh water and salt water. The process is based in the osmotic principle; it occurs due to the contact of fresh water and saline water via a semipermeable membrane, which is permeable to water but not to salt [32]. The greater the difference in salinity between the two bodies of water and the smaller the distance at which these differences occur, the greater is the salinity gradient. While greater is the difference in salinity between both water flows and less is the distance that occurs with these differences, the greater is the salinity gradient. The membranes of these systems are still in the research and development phase; its efficiency is important since it requires selective membranes, and low electrical accumulation [33]. Two salinity gradient ocean (SGO) technologies have been developed at the pilot scale: Reverse electrodialysis (RED) and pressure retarded osmosis (PRO) [34]. The first generates a voltage by differences of positive and negative charges, similar to a battery. In the PRO, the membrane generates a current that can move a turbine.

### 3. Methodology

#### LCA Methodology

Life cycle assessment (LCA) analyses quantitatively account for all the energy, materials, emissions and waste products associated with everything from the extraction of raw materials to disposal at the end of the use of technology [20,35]. An LCA allows a decision-maker to study an entire system, in addition, to compare the environmental impacts of systems or technologies that have an equivalent function or performance [20,21]. The LCA process is regulated by the International Standards Organization (ISO) 14,000 series: ISO 14040: 2006 (Environmental Management-Life Cycle Assessment-Principles and Framework) and ISO 14044: 2006 (Environmental Management-Life Cycle Assessment-Requirements and Guidelines). The LCA methodology is an iterative process that consists of four stages (all of them interrelated): Objective and scope; life cycle inventory; life cycle impact evaluation and interpretation of results (Figure 1). The LCA method for the assessment of energy systems could be a useful and universally applicable tool for the monitoring and assessment of proposed energy systems as it can indicate areas that have a significant impact on the environment [5].



**Figure 1.** Life cycle assessment (LCA) structure. Adapted from ISO 140403.2. Review Methodology.

To achieve the objective of this review, a systematic analysis was undertaken to identify and assess all LCA studies of ocean energy systems reported in literature from 2007 to 2019. The methodology for this literature search is shown in Figure 2, and includes the three-step practical screening conducted. This review was based on the standardized technique for assessing and reporting reviews of LCA by Zumsteg et al. [36]. First, two inclusion criteria were applied: Articles must be in English and must have been published between 2007–2019 (since during the last decade there has been reflected a major attention to the environmental impact assessment generated by these new technologies). The relevant literature was searched in different search engines of major publishers (Science Direct, Springer link, Emerald, IEEEExplore). The search engine Google Scholar was used to include studies that were not published in journals. Searches were started with various keywords in an iterative process, such as: Life cycle assessment and its synonyms (LCA and life cycle analysis), ocean energy, wave energy, tidal energy, thermal energy and saline gradient. In the initial search, 2358 studies were identified considering the diverse keywords for our systematic review. A second screening was based on information derived from titles and abstracts, in this stage 112 relevant studies were identified. In the final count, potential articles selection was focused on the LCA methodology and inclusion criterion (all types of ocean energy). Lastly, the literature review involved 18 potential LCA studies of ocean energy; nine scientific papers published in international peer-reviewed journals, five post-graduate theses (four master and one bachelor’s degree) and four papers presented at conference congress. The studies considered in the present review allowed for obtaining a global environmental assessment

of the ocean energy generation systems in the different stages of their life cycle that could be used to guide the research and development of these systems.

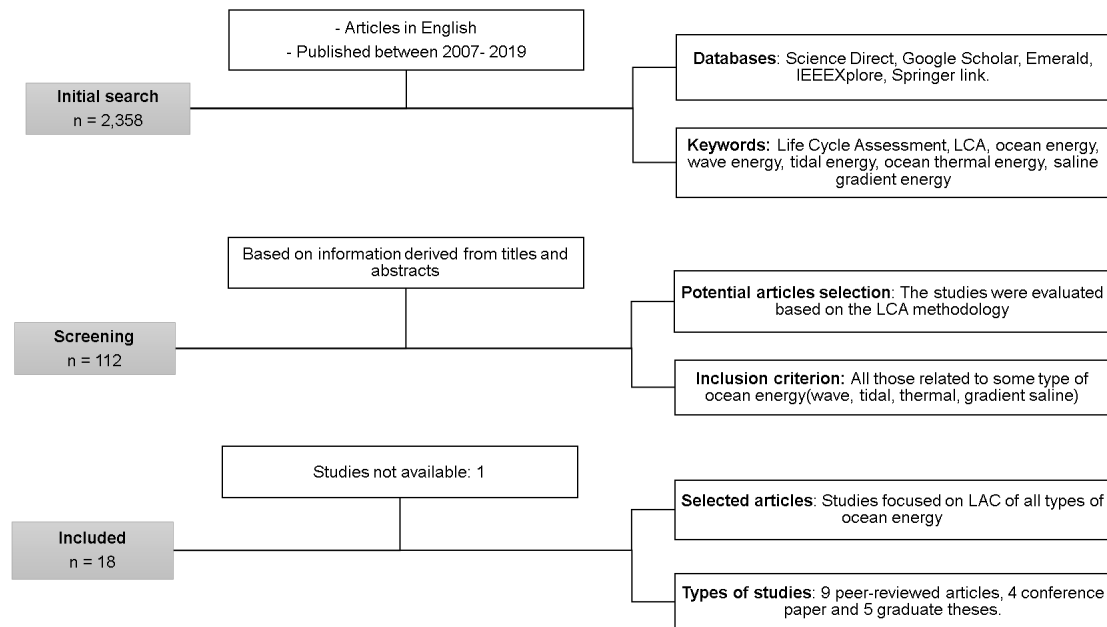


Figure 2. Systematic methodology review.

In this review, the results are presented by a type of technology used for ocean energy generation, which includes: Wave, tidal and thermal energy. Although the energy generation by saline gradient was also considered in the bibliographic review, there is no information available regarding to LCA studies on this technology (Figure 3).

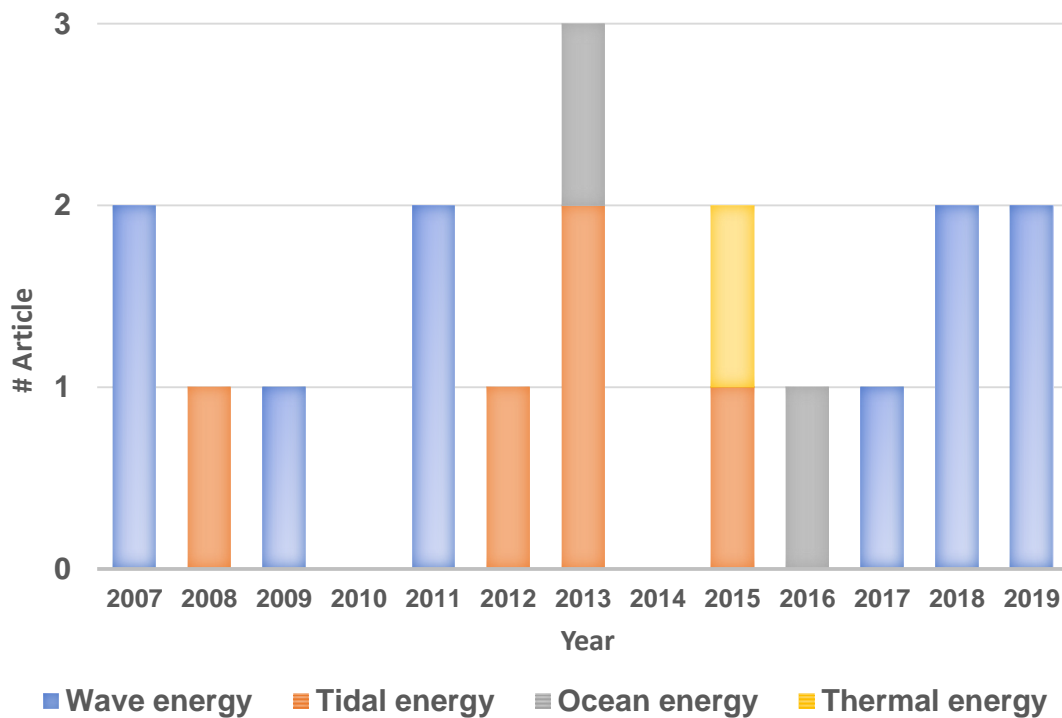


Figure 3. Number of published studies about LCA of ocean energies from 2007 until 2019.

## 4. Results and Discussion

### 4.1. LCA on Ocean Energy Technologies

In the last two decades, LCA methodology has been widely applied to evaluate the environmental impacts of energy generation systems [37–44], as well as individual technologies [45–48]. So far, only a few LCA have been performed on ocean energy systems with a focus on full-scale prototypes and good environmental performance relative to conventional power plants [12,14,49,50]. Furthermore, most of the papers involve the application of new ocean energy technologies focused on embodied energy and carbon emissions, and only some of them give a complete environmental evaluation. To date, tidal and wave energy are the most developed kinds of ocean energy and have been identified as the technologies with the highest potential to offer a significant contribution to countries with ocean resource in the medium to long term [12–14].

It is important to highlight that 11 of the 18 studies analyzed concentrate only on carbon emissions and embodied energy [26,29,49–57] and the rest give a more detailed evaluation including other environmental impact categories [9,12,58–62]. In general, scientific papers and surveys provided information about LCA of ocean energy studies, considering different operating criteria, geographical area, and costs, among others. The environmental impact categories, the impact assessment method, and the functional unit (FU) considered for each LCA study analyzed have been included in Table 1. The functional unit of all projects is 1 kWh of electricity delivered, similar to what has been established as FU in other LCA studies on power generation systems in order to be consistent throughout the study so that the results can be comparable and provide useful information for the energy sector [12,29,63]. On the other hand, the life time depends on the type of technology, generally the wave energy systems have a low life time compared to OTEC technology due to the type of infrastructure (equipment, power connections, structural components) of each device, as well as, the operating and maintenance conditions. The LCA studies include all life cycle stages (assembly, installation, operation and maintenance, final disposition) and in some cases, also involve the mooring and foundation stages, and the cable connection to the grid.

**Table 1.** LCA studies of ocean energy technologies.

Type	Device	Objective	Functional Unit (FU) (kWh)	Scope	Life Cycle Impact Assessment Method	Impact Categories	Lifetime (Year)	Reference
Ocean overall	Wave energy converters (WEC)/Ocean thermal energy conversion (OTEC)/Tidal	To estimate the greenhouse gas (GHG) emissions and the energy payback period of the three ocean energy systems.	1	Cradle-to-grave	CO <sub>2</sub> emissions aggregated	Energy use and CO <sub>2</sub> intensities	WEC: 20/50 OTEC: 30 Tidal: 100	[54]
	Overtopping Breakwater for Energy Conversion (OBREC) WEC	An LCA applied to OBREC WEC in terms of carbon footprint.	One single module <sup>a</sup>	Cradle-to-grave	CO <sub>2</sub> emissions aggregated	CO <sub>2</sub> emissions	60	[57]
	Pelamis WEC	A full LCA of the first-generation Pelamis WEC through a wide range of environmental impacts categories.	1	Cradle-to-grave	ReCiPe and CED methods	1, 2, 4–6, 9–11, 13, 18–22, 26–28, 34, 35	20	[62]
	Point absorber WEC	To compare two different Point absorber WEC through simplified LCA methodology	-	Cradle- to -grave	—	4, 6, 10, 13, 19, 31	—	[61]
Wave	Buoy-rope-drum WEC	An LCA was conducted for a Buoy-rope-drum WEC by eco-labeling its life cycle stages and processes.	1	Cradle-to-grave	ReCiPe method	1, 2, 4, 6, 9–11, 15, 18–22, 26–28, 34, 35	20	[9]
	Point absorber WEC	An assessment of the environmental impacts was made in terms of climate change of a point absorber WEC through the LCA methodology.	1	Cradle-to-grave	CO <sub>2</sub> emissions aggregated	CO <sub>2</sub> emissions	5	[56]
	Pelamis WEC	This study builds upon the work carried out by Parker et al. (2007) but this includes a full assessment of the life cycle environmental impacts the Pelamis WEC.	1	Cradle-to-grave	EDIP LCA method <sup>b</sup>	1, 3, 4, 6–8, 11–15, 26, 29, 31–33	20	[60]
	Point absorber WEC	An LCA of a hypothetical prototype wave power plant was done.	1	Cradle-to-grave	EPD LCA method <sup>c</sup>	1, 4, 11, 23, 26, 28, 30, 36	20	[59]
	Wave Dragon WEC	An LCA was conducted for a wave dragon converter, considering all the lifecycle stages.	1	Cradle-to-grave	EDIP LCA method <sup>d</sup>	1, 3, 4, 6–8, 12–15, 24–26, 28	50	[58]
	Pelamis P1	This paper presents an analysis of life cycle energy use and CO <sub>2</sub> emissions associated with the first generation of Pelamis converters.	1	Cradle-to-grave	CO <sub>2</sub> emissions aggregated	Energy use and CO <sub>2</sub> intensities	20	[49]

Table 1. Cont.

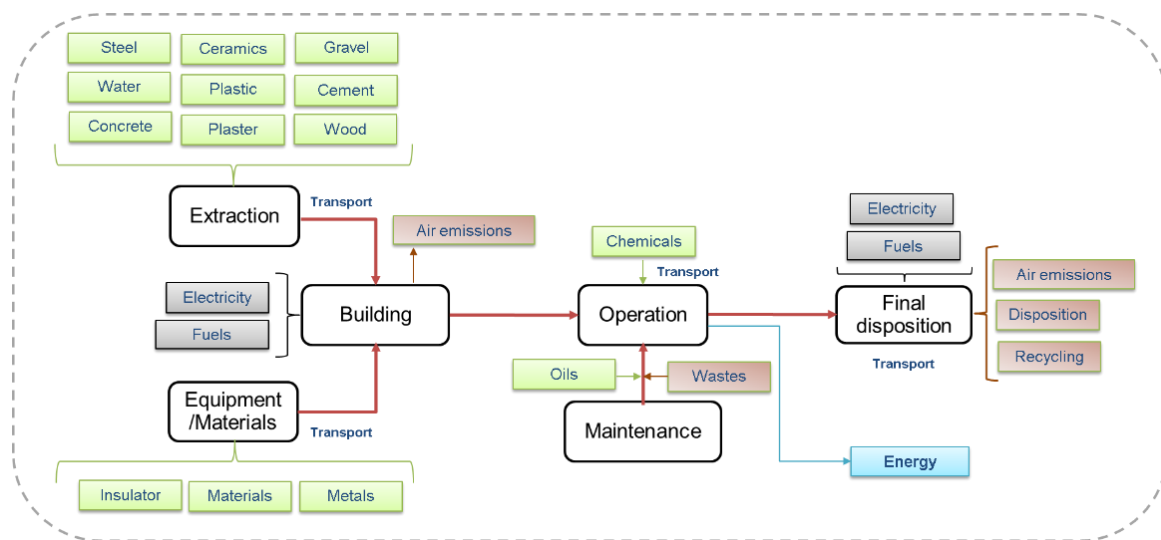
Type	Device	Objective	Functional Unit (FU) (kWh)	Scope	Life Cycle Impact Assessment Method	Impact Categories	Lifetime (Year)	Reference
Tidal	Swansea Bay Tidal Lagoon	To assess the embodied energy and CO <sub>2</sub> emissions of tidal lagoon from the LCA overview	1	Cradle-to-gate <sup>e</sup>	CO <sub>2</sub> emissions aggregated	Energy use and CO <sub>2</sub> intensities	120	[26]
	Four tidal devices	To assess the embodied energy and CO <sub>2</sub> emissions of four tidal energy devices through the LCA methodology	10 MW	Cradle-to-grave	CO <sub>2</sub> emissions aggregated	Energy use and CO <sub>2</sub> intensities	100	[55]
	Deep Green Tidal	To determine the Energy payback time and CO <sub>2</sub> emissions associated with the life cycle of Deep Green	1	Cradle-to-grave	CO <sub>2</sub> emissions aggregated	Energy use and CO <sub>2</sub> intensities	20	[53]
	Tidal Severn barrage	To estimate the total potential energy demand and carbon emissions of the Severn barrage using LCA methodology.	1	Cradle-to-grave	CO <sub>2</sub> emissions aggregated	Energy use and CO <sub>2</sub> intensities	120	[52]
	Seagen Marine Current Turbine	To analyze the life cycle energy use and CO <sub>2</sub> emissions associated with the first generation of Seagen marine current turbines	1	Cradle-to-grave	CO <sub>2</sub> emissions aggregated	Energy use and CO <sub>2</sub> intensities	20	[50]
Wave/Tidal	Point absorber WEC/Horizontal axis turbine	To assess the environmental impacts of tidal (horizontal axis turbine) and wave (point absorber) energy device producing electricity and delivering it to the European electricity network through the LCA methodology.	1	Cradle-to-grave	ILCD <sup>f</sup>	1, 4, 10, 11, 16–18, 20, 26–28, 31, 33	20	[12]
	Oyster WEC/SeaGen turbine	To perform an LCA of a wave energy device (Oyster) to determine the embodied energy and carbon emissions and to compare results with a tidal energy device (SeaGen).	1	Cradle-to-grave	CO <sub>2</sub> emissions aggregated	Energy use and CO <sub>2</sub> intensities	15	[51]
Thermal	OTEC	To assess the CO <sub>2</sub> emissions of the OTEC using the LCA method.	1	Cradle-to-grave	CO <sub>2</sub> emissions aggregated	Energy use and CO <sub>2</sub> intensities	30	[29]

1. Global warming; 2. Acidification; 3. Ozone depletion; 4. Photochemical oxidation; 5. Human toxicity air; 6. Human toxicity water; 7. Human toxicity soil; 8. Nutrient enrichment; 9. Ecotoxicity water chronic; 10. Ecotoxicity water acute; 11. Ecotoxicity soil chronic; 12. Slag and ashes; 13. Nuclear waste; 14. Hazardous waste; 15. Bulk waste; 16. Eutrophication; 17. Non-renewable use; 18. Renewable energy use; 19. Water use; 20. Radioactive waste; 21. Resources (all); 22. Freshwater ecotoxicity 23. Particulate matter/respiratory inorganics; 24. Ionizing radiation (human health), 25. Human toxicity, cancer effects; 26. Human toxicity, non-cancer effects; 27. Resource depletion; 28. Fossil depletion; 29. Marine ecotoxicity; 30. Agricultural land occupation; 31. Urban land occupation; 32. Natural land transformation; 33. Water depletion; 34. Metal depletion; 35. Cumulative energy demand (CED).<sup>a</sup> The FU is represented by one single module (5 m seafront length) embedding the one module of OBREC WEC; <sup>b</sup> Based on Hauschild and Potting [64]; <sup>c</sup> Based on International EPD Cooperation [65]; <sup>d</sup> Based on Wenzel et al. [66]; <sup>e</sup> Four stages were considered: Material production, transport, construction and operation; <sup>f</sup> Based on Hauschild et al. [67].



#### 4.2. Life Cycle Inventory for Ocean Energy Technologies

Life cycle inventory (LCI) involves collecting input and output data for all unit processes of WEC devices. LCI includes two aspects of data collection; primary data and secondary data [68]. Primary data are directly related to the plant’s life cycle and they are collected from the design report for the plant and staff of the plant. Secondary data are the life cycle burdens of the former inputs, such as equipment manufacturing, transportation, and electricity generation. These data are regularly collected from international database platforms or previous LCA studies [29,69]. The LCI database allows an in-depth review of the state-of-the-art of ocean energy technologies, paying attention to the different technology components, such as foundations, moorings and storage systems (Figure 4). The European Commission’s Joint Research Centre (JRC) developed a detailed database with technical information on global ocean energy devices that have been tested or deployed in real-water conditions [14]. The Table 2 shows the LCI with the main characteristics of the ocean energy systems evaluated in the LCA studies.



**Figure 4.** Overall schemes of life cycle inventory (LCI) of the energy ocean system.

**Table 2.** Characteristics of the ocean energy devices evaluated in the LCA studies.

Device Name (Developer)	Description/Operating Principle	Components	Reference
Pelamis WEC/wave dragon WEC/climate change (CC)-OTEC/Servern barrage	<b>Pelamis P1.</b> Cylindrical type WEC consisting of semi submerged structure with cylindrical sections linked by hinged joints.	<b>Pelamis 1 WEC.</b> Tube sections and power conversion modules [49].	[54]
	<b>Wave Dragon WEC.</b> Overtopping type of WEC. It focuses the incoming waves towards a huge reservoir with two wave reflectors to run a number of turbines by converting the water pressure to power generation.	<b>Wave Dragon WEC.</b> Turbines, wave reflectors and platform [70].	
	<b>CC-OTEC.</b> Electricity is generated utilizing the small temperature difference between warm surface seawater and deep cold seawater.	<b>CC-OTEC.</b> Rankin cycle heat engine [71].	
	<b>Servern Barrage.</b> It consists in the construction of a 15–18 km long barrage in UK.	<b>Servern Barrage.</b> Barrages series, creating a basin area of 480 km <sup>2</sup>	
<b>Wave Energy</b>			
Overtopping breakwater for energy conversion (OBREC WEC) (Interreg Med Maestrale)	This device is a full-scale WEC prototype integrated into an existing breakwater. It was designed to capture overtopping waves and produce electricity. The OBREC WEC converts the wave overtopping process into potential energy by collecting seawater in upper reservoirs to feed a set of mini hydro-turbines. Electricity is produced by means of a generator linked to the turbines.	The prototype consists in a single module (5 m sea front length). The module embeds a set of hydro-turbine.	[57]
Pelamis WEC (Pelamis Wave Power Ltd.)	Floating oscillating body system of the attenuator type. Pelamis WEC extracts energy from the oscillation induced by the wave motion on separate sections of tube.	This device is 120 m long and 3.5 m in diameter. It has four cylindrical steel tube sections linked by three power conversion modules (PCMs) at the hinged joints. The components are: Nose, mid and end tube; yoke, yaw restraint line.	[62]
Point absorber I/II WEC (University of Palermo)	The external buoy is used to collect the mechanical energy of the sea waves and transfers it into electricity through the electrical generators, installed inside the central buoy. <b>Point absorber I.</b> The mechanical energy (vertical motion) is converted into electrical energy through linear permanent magnet generators. <b>Point Absorber II.</b> The mechanical energy (vertical motion inside the central buoy) is transformed into a unidirectional rotary motion by using freewheels and a bifacial rack.	The devices included: Lamp, photovoltaic panel, central buoy, external buoy, ballast, jumper buoy, four moorings.	[61]
Buoy-rope-drum (BRD) WEC (Shandong University, Weihai).	BRD WEC consists in a rope with its lower end connected to a gravity anchor on the seabed is attached and wound around the drum of the generator casing. The wave energy extraction and energy conversion mechanism consist of two primary strokes. During this stroke, wave energy is extracted and to electrical energy.	The BRD WEC consists of three main functional modules including: Buoy, spring, drum, generator, rope, mooring chain and anchor.	[9]

Table 2. Cont.

Device Name (Developer)	Description/Operating Principle	Components	Reference
Point absorber WEC (Royal Institute of Technology, Stockholm, Sweden)	The WEC consist of a floating structure that absorbs energy in every direction by its movement at the water surface, it converts the buoyant motion top relative to the base into electrical power.	<p>The device is divided into three different modules:</p> <ul style="list-style-type: none"> <li>- <b>Buoy module.</b> It is used to extract as much energy as possible from arriving waves and includes the generator inside.</li> <li>- <b>Generator module.</b> Transverse flux generator machine.</li> <li>- <b>Mooring system module.</b> Set of chain connected to an anchor, with the aim of keeping the floating structure in place.</li> </ul>	[56]
Eight WEC types (fifty different developers)	The wave energy is the energy produced by the movement of the waves which is generated by the action of the wind on the sea surface. The devices studied were: Attenuator; point absorber; oscillating wave surge; oscillating water column; overtopping device; pressure differential; rotating mass; others.	<p>The devices are divided into:</p> <ul style="list-style-type: none"> <li>- <b>Structural components.</b> Float, Oscillating Water Column (OWC) chamber, basin, spar, plate.</li> <li>- <b>Power take-off.</b> Hydraulic, mechanical and control systems, shaft, gearbox, generator and, auxiliaries.</li> <li>- <b>Mooring and foundations.</b> Mooring lines, pontoon, support tower, anchor, gravity base, pile.</li> <li>- <b>Electrical connection.</b> Cable, connector, hub.</li> </ul>	[12]
Oyster WEC (aqua marine power)	The device incorporates a base section and a moving flap, joined by a connector and two hydraulic rams. As the flap moves in wave motion, water is pushed through the pipe flow lines and to the onshore power system, which is contained within two shipping containers.	The device included: Flap, connector, seabed frame, rams, pipeline and electrical power conversion.	[51]
Pelamis WEC Second-generation (P2) (European Marine Energy Centre)	Pelamis is a semi-submerged snake-like offshore wave energy converter. Three power conversion modules (PCMs) sit between the tube sections and house the hydraulic power take-off, generators and control equipment.	The device is divided into two different modules: <b>Structure of the Pelamis.</b> Cylindrical steel tube sections with sand used as ballast. <b>Mooring and cabling system.</b> It includes several plastic components, electrical equipment, housed in the nose tube, collects and transforms the power to high voltage for export to shore. The hydraulic power-take-off, generators and control equipment are in the PCMs.	[60]
Wave power plant (WPP) prototype (Seabased Industry AB)	The studied WPP prototype consists of 1000 generators, placed in arrays of 50 units. Each array is connected by a sea cable to a low voltage marine substation (LVMS) which in turn is connected to a medium voltage substation (MVMS).	The device included: Buoy, wire rope, end stops, stator, translator, springs.	[59]

Table 2. Cont.

Device Name (Developer)	Description/Operating Principle	Components	Reference
Wave Dragon (Technical University Denmark)	Wave Dragon is a floating wave energy converter functioning by extracting energy principally by means of waves overtopping into a reservoir. A 1:4:5 scale prototype has been tested for 21 months in corresponding sea conditions at a less energetic site.	The devices included: cables connection, monitoring, electronic devices, turbines, generators, platform.	[58]
Pelamis 1 Ocean (Power Delivery, Portugal)	Semi-submerged WEC (offshore) and was the world’s first commercial wave farm. The first versions are 120 m long, 3.5 m in diameter and rated at 750 kW.	The devices included: Tube sections, power conversion modules, yoke, hydraulic systems, electrical and electronic systems	[49]
<b>Tidal Energy</b>			
Seven tidal energy devices	Tidal energy is generated by the difference between low and high tides, as result of the interaction of the gravity of the sun, earth, and moon. The devices studied were: Horizontal and vertical axis turbine; oscillating hydrofoil, enclosed tips, Arquimedes screw, tidal kite, others.	The structural components of tidal devices are: Rotor (the most common component), duct, nacelle, flap/fin, helix, pod or ballast (rarely used).	[12]
Swansea Bay Tidal Lagoon (Tidal Lagoon Swansea Bay plc)	The technology combines the large-scale production potential of tidal barrages with the lower environmental impact of in stream turbines. In this case, only a small section of the estuary is cut off, forming a lagoon, which can be flooded and drained with the rising and falling tides.	The tidal lagoon technology involves 9.5 km sea wall, which enclose 11.5 km <sup>2</sup> of the bay. The sea wall contains 16 turbines and 8 sluice gates which allow water to pass through both on the rising and falling tide.	[26]
Four tidal devices	<b>Tidal Generation Ltd. (TGL).</b> It is a tri-blade single turbine device.	<b>Tidal Generation Ltd.</b> The components are: Three blades, turbine and piles as support. The body and foundations of the device are constructed mainly from steel.	[55]
	<b>Open Hydro.</b> This device is an open center horizontal axis multi-blade turbine with a ducted housing.	<b>Open Hydro.</b> The structural components are: multi blade and open center turbine. The device is constructed largely from steel, with glass reinforced plastic blades.	
	<b>ScotRenewables.</b> It is a floating twin horizontal axis turbine device.	<b>ScotRenewables</b> is composed by turbine, cable moorings and composite blades.	
	<b>Flumill.</b> This device is an original twin Archimedes’ screw design.	<b>Flumill.</b> Two principal components: twin Archimedes screw and monopile foundation.	
Deep Green Tidal (Minesto)	The device generates electricity from low velocity flowing water in. Energy, harnessed in, is transferred to the turbine, the electricity is then generated by the generator which is attached to the turbine.	The device composed of a wing, nacelle, turbine, generator. The complete unit is attached to a foundation at the seabed by struts and a tether. The deep green is steered in a trajectory by a rudder and a servo system.	[53]

**Table 2.** *Cont.*

Device Name (Developer)	Description/Operating Principle	Components	Reference
Tidal Severn Barrage (Tidal Power Group)	The scheme included the Severn tidal estuary and a chain of water wheels. The sluice gates of Severn barrage allow the tide to flow, during high tide they close, storing large amounts of water behind the barriers.	The scheme consists of sluice gates, barrage, basin, low and high tide and turbine. The components of hydraulic ram systems are: Hydraulic rams, calipers, support frame, roller bearing, bearing cradle, water wheel and brake disc.	[52]
Seagen Turbine (Marine Current Turbines Ltd.)	SeaGen is a tidal energy device that converts energy from tidal flow into electricity. The device produces mechanical power by converting the kinetic energy from water currents. This technology was the first generation of Seagen turbines with 1.2 MW grid connected system.	The device included: Twin 16m diameter axial flow rotors, blades, crossbeam, steel monopile, platform, pod sit, generator and tower.	[50]
<b>OTEC energy</b>			
OTEC (Delft University of Technology)	The operating principle of the OTEC plant is based on a thermodynamic cycle in which a working fluid is used that evaporates at fairly low temperatures. The working fluid is a mixture of ammonia and water. The mixture is pumped through the evaporator in which the warm seawater evaporates the mixture. This evaporated mixture fills a turbine and the mixture expands. Subsequently, the mixture flows through the condenser, which converts the gas into a fluid mixture.	The OTEC components are: Plate heat exchanger, working fluid, storage tanks, piping, water pipes, platform, chains, wire, turbine, generator and power distribution.	[29]

### 4.3. Life Cycle Assessment of Ocean Energy Technologies

As mentioned above, most LCA studies focus on carbon life cycle assessment, only a few of them perform a global evaluation integrating other impact categories. Besides, all of these are focused on wave energy (seven of 18 published articles). Until now, there have been no studies in the literature that present a comprehensive evaluation of LCA regarding other types of ocean energy (tidal, thermal and gradient salinity). Even though the results from this comprehensive review show the available information about the life cycle environmental assessment of ocean power systems, it is important to mention that the data and information are diverse, mainly due to structural components, size (nominal capacity), design device and type of technology. Although seven articles with evaluation of different impact categories are reported, only three of them show net values of the impact categories evaluated (with different units) [59,60,62]. The remaining five do not present results that can contribute to the making of comparisons between devices, and only show environmental impacts generated by a kind of material or device mass, in percentage or even by units of equivalent persons [9,12,58,61]. Hence, comparisons of environmental impacts between devices is limited.

#### Life Cycle Impact Assessment of Wave Energy Technologies

As it is well known, wave energy represents a strategic option for renewable energy systems in the foreseeable future [61]. Overall, all the authors agree that most of the environmental impacts obtained by this type of system (point absorbers WEC, wave dragon, Pelamis WEC; buoy-rope-drum (BRD) WEC) are presented in the manufacturing stage of the device [9,12,58–60]. These environmental impacts are caused mainly by structural components (turbine propellers, buoy structure, turbines), energy consumption, mooring foundations and the materials used to manufacture the devices, among which are: Stainless steel, tin, steel parts, concrete, and cast iron. These impacts can represent between 40% and 90% of the total impacts obtained during their life cycle [9,12,59]. The categories that have a greater impact, include: Climate change, resource depletion, aquatic eutrophication, human toxicity water, ecotoxicity water, hazardous waste, ozone depletion, terrestrial acidification, freshwater eutrophication, photochemical oxidant formation, particulate matter formation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion, and fossil depletion [9,12,60]. Particularly, the steelmaking processes have a significant impact in freshwater eutrophication, freshwater and marine ecotoxicity [62]. In addition, power takeoff (PTO) components play a significant role in three impact categories: Ionizing radiation, freshwater eutrophication and terrestrial ecotoxicity [9,12]. In this case, freshwater eutrophication impacts are generated by materials manufacturing used for cables in the electrical connection, such as: Polycarbonate, copper and stainless steel (mooring and foundations stages). The ionizing radiation impacts come from production of electronics (assembly stage) and terrestrial ecotoxicity due to permanent magnet [12]. Additionally, the shipping operations related with operation and maintenance also contributing significantly in some categories, such as: Ozone depletion, terrestrial eutrophication and acidification, photochemical oxidant formation, and natural land transformation [60,62].

Furthermore, the environmental impacts generated by assembly, installation, operation and maintenance are not significant. The total contribution from these stages, ranges from one to over forty percent [9,12,59,62]. It is important to mention that within the analyzed LCA studies, two devices that operate in real-sea environments are considered, with similar findings [58,62]. However, Moan [72] mentions in his study on life cycle structural management of offshore structures, such as offshore gas and oil structures, that a design reassessment is required during the operation stage considering operational restrictions, repair and maintenance inspections due to possible changes of the offshore structure function, updated knowledge about environmental loads or damages, as well as, expected life time. In addition, several authors have remarked on the importance of contemplating the impacts generated during the service life of these devices in the ocean [58,62,73]. Moan [73] reports that operational experiences show that several safety measures are required to control the risks associated with different environmental hazards in offshore structures. Until now, few LCA studies that consider

devices deployed under real operating conditions establish that during the operation stage, more ecological research is required to determine the potential environmental impact on marine life, and this information will allow improvements in environmental monitoring standards and best practices for OET design [58,62,74]. Among the potential impacts that have been reported during the operation stage are scour, physical benthic habitat disturbance, operational noise, water flow patterns, pollution of antifoulants, sediment mobilization, collision and other risk for marine animal and birds [74,75]. Regarding the last stage, the disposal of the components structure presents an impact on the categories of marine eutrophication, natural land transformation, freshwater, and marine ecotoxicity, and these impacts are generated mainly by waste treatment and management [9,62]. The life cycle impact assessments show that the most important avoided impacts are acidification, bulk waste, human toxicity, soil and global warming mainly associated with the electricity production from WEC devices due to fossil fuel consumption and, hence, GHG emissions and other chemical compounds [58].

In this sense, the search for alternative efficient and environmentally sustainable structure materials for the device manufacture is an improvement opportunity to reduce the environmental performance of these technologies [49]. The device developers should focus on reducing the amount of steel in the new structural designs used in the manufacturing process [59,62]. Besides, efficient shipping operations for installation, maintenance and decommissioning should be considered, utilizing more fuel-efficient transportation methods or reducing the frequency of maintenance operations [62]. Another aspect to consider is the potential to recycle structure materials. This could be a significant environmental improvement, avoiding the environmental impacts of waste management and also the impacts that are associated with raw material extraction [60]. These actions could reduce the overall life cycle environmental impacts of WEC technologies [9,60].

In addition, the assessment of different scenarios to increase environmental improvement in these systems is essential, evaluating of critical factors such as: Increased efficiency or durability (capacity factor and lifetime), other mooring structures (using mooring lines), and reduced offshore distance (do not use longer cable connection) [12]. For instance, Soerensen et al. [58] in a sensitivity analysis evaluated various parameters (the lifetime of different components, the power production achieved, wave height, maintenance) obtaining as a result that when the lifetime of WEC (Wave Dragon) increased, the global electricity production increment and more resource consumptions and environmental impacts were avoided. Parker et al. [49] evaluated two alternative materials as a partial replacement of the steel structure, particularly; concrete and glass-reinforced plastic (GRP); in this case, the climate change category was reduced using these alternate materials. Uihlein [12] conducted a sensitivity analysis with different steel types for structural components manufacture; the results showed that the significant environmental impacts would be much lower. Zhai et al. [9] performed a sensitivity analysis varying the capacity factor (defined as the actual electricity production divided by the maximum possible electricity output of a power plant, over a period of time [76]) values (20–50%), the results showed that climate change category decrease with the increase of capacity factor. Further, Thomson et al. [62] reported that an increase in design life and shortening offshore distance could reduce global environmental impacts significantly.

#### 4.4. Life Cycle Carbon Emissions Assessment

As mentioned earlier, most of the papers concentrate only on carbon emissions and embodied energy (11 of 18 published articles) (Table 1) [49–51,54,56]. The articles focused on these topics are in line with the current global situation regarding increased energy demand, the use of renewable energy sources, and climate change. In this context, ocean energy represents a promising worldwide transition to a low-carbon electricity system [49,57]. This section involves a thorough life cycle carbon emission assessment of the all different devices evaluated, considering the technologies of each system.

The general results show that the manufacture of materials used in the structure (particularly, steel manufacturing, in most cases), mooring and foundations, and the shipping operations have the greatest impact on total CO<sub>2</sub> emissions (between 40–95% of the total emissions) [12,26,49,50,60].

Walker and Howell [51] evaluated an Oyster WEC device; the assessment included CO<sub>2</sub> emissions from materials, manufacture, transport, installation, operation, maintenance and decommissioning (including recycling). According to the results, the manufacture materials stages represent the more than 95% of the total emissions. Douglas et al. [50] reported a life cycle carbon emission of Seagen turbines; the results showed that the most significant stage was the materials extraction and manufacturing stage, accounting for 86% of total emissions. Elmeahag and Torosian [53] presented that foundation and structural components account for 86% of the total emissions of a Deep Green tidal device. In this case, the manufacturing stage is the one that contributes most to environmental impact. Walker et al. [55] evaluated four tidal devices (two three blade horizontal axes, a multi-blade turbine and an Archimedes screw device): The results obtained are similar to previous authors. The materials and manufacture stage present the greatest impacts in terms of CO<sub>2</sub> emissions for the four devices. Another similar instance is reported by Aalberts [29] evaluating OTEC technology. The results show that the raw materials extraction stage is the one that presents a greater contribution of CO<sub>2</sub> emissions, in particular, the platform structure is the biggest contributor in the climate change category (more than 50% of total emissions), and this is mainly due to the large amount of steel that is required. Gastelum [56] evaluated the total environmental impact in terms of climate change of a new model of point absorber WEC; the evaluation was done by the three modules: Buoy, generator and mooring system. The results of the whole system show that the polyurethane buoy manufacturing process contributes to 60% of total CO<sub>2</sub> emissions, which is attributed mainly to the materials used to manufacture the buoy (steel rolling) and the shipping operations. Another similar study was conducted by Patrizi et al. [57] evaluating an OBREC WEC device; the results shows that 82% of the total CO<sub>2</sub> emissions is due to the use of materials for the components construction (including structural elements, ramp, foundations and cables for the connection to the grid). Notably, 51% of the emissions are due to the electrical connection, and to the terrestrial cable (copper and iron major components). These findings are similar to what was reported by Parker et al. [49], Thomson et al. [60] and Uihlein [12].

In this context, environmental improvements can be reached by increased structural materials efficiency and the use of alternative installation methods to increase steel recovery in the dismantling stage. The LCA studies report that the recycling process in the final disposal stage has a significant reduction in CO<sub>2</sub> emissions [50,55]. For instance, Elmeahag and Torosian [53] evaluated alternate materials for the different components of the deep green tidal device. The results showed that it is possible to reduce emissions by 30 to 50% depending on the evaluated structure. Walker et al. [55] performed a sensitivity analysis in order to understand the effect of total CO<sub>2</sub> emissions variation if the amount of structural materials (steel and cement) would be adjusted ( $\pm 5\%$ ) due to its significant contribution to overall values. The results showed that the variation from original values led to a change of between 2.5% and 3.5% lower in CO<sub>2</sub> emissions of the functional unit, a significant percentage to be considered. Aalberts [29] evaluated diverse scenarios, one of them was to assume that 90% of primary materials (steel and titanium) will be recycled. This option reduces CO<sub>2</sub> emissions by 25%. Another proposed scenario was to increase the production scale (10 MW to 100 MW); the overall results of this method show a 57% reduction in CO<sub>2</sub> emissions, and the contribution of the platform structure together with the mooring was much smaller than with 10 MW OTEC.

In the same way as the other impact categories, the other life cycle stages (assembly, installation, operation and end of life) have almost a negligible impact on global warming [12]. This is supported by other LCA evaluations regarding ocean energy technologies [12,49,62] demonstrating that most of their climate change impact are related to materials of structural components such as the installation, operation and maintenance stages of devices [57]. With the exception of Kelly et al. [52], when they performed the carbon emissions assessment of the tidal Severn barrage. In this study, the operation stage was identified as the stage with the greatest contribution. This is mainly due to the fact that for this type of device whilst during the operation stage there are direct and auxiliary energy processes, such as: Flood pumping and an auxiliary power plant for running the plant.



**Table 3.** Emission of gases in term of g CO<sub>2</sub> eq/kWh by ocean energy devices.

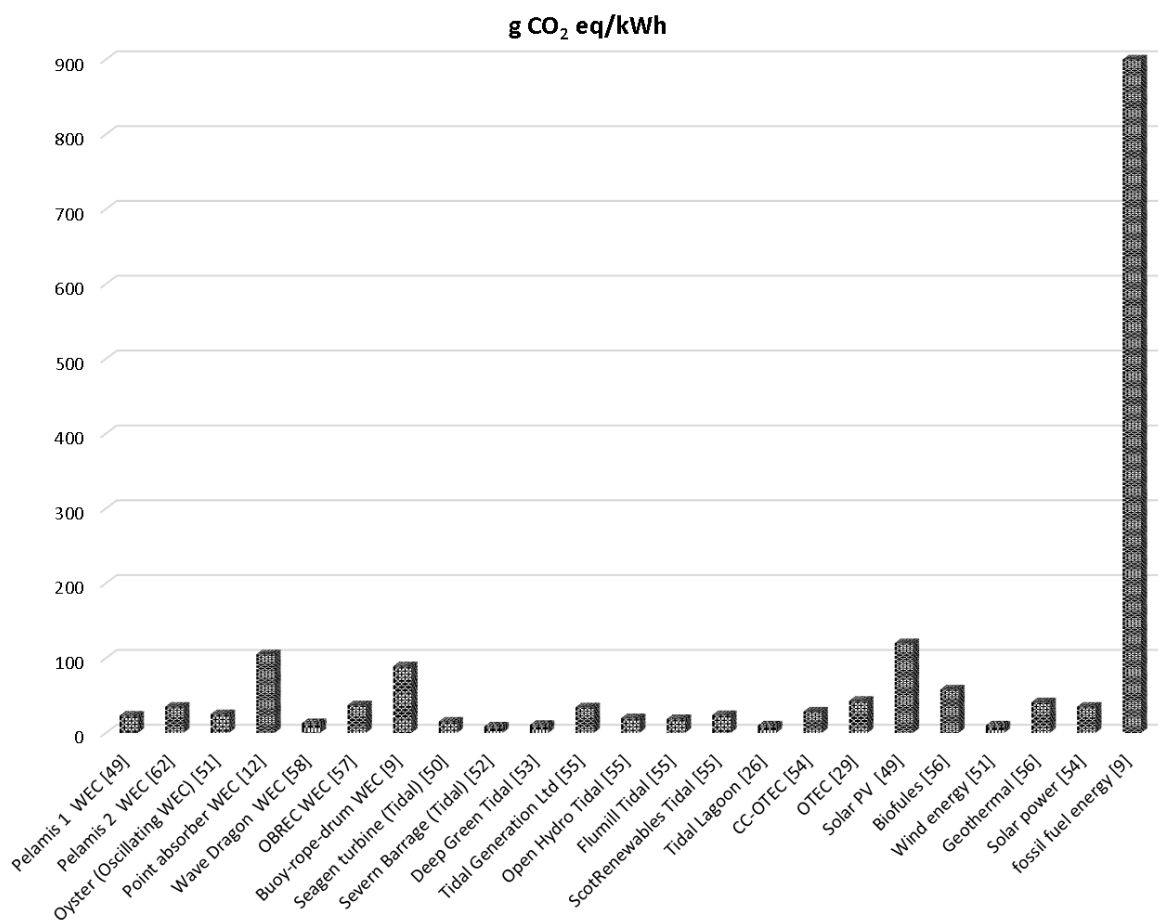
Device Type	[49]	[58]	[50]	[59]	[60]	[51]	[52]	[55]	[53]	[54]	[26]	[29]	[12]	[56]	[9]	[62]	[57]
Pelamis WEC	23				30					20			44				35
Oyster WEC						25							64				
Point absorber WEC				39–126									105	30–80			
Wave Dragon WEC		13									28						
Buoy-rope-drum WEC															89		
OBREC WEC																	37
Seagen turbine			15			15							23				
Tidal Severn barrage							8.6 *										
Deep Green Tidal										10.7							
Tidal Generation Ltd.								34.2									
Open Hydro								19.6									
Flumill								18.5									
ScotRenewables								23.8									
Tidal Lagoon													10				
OTEC energy										28.5		42.8					

\* Without flood pumping process.

Table 3 shows a compilation of the CO<sub>2</sub> emissions of the different devices evaluated. The difference of values between devices evaluated may well be due to the specific features and properties considered, such as: Structural components, manufacturing materials, PTO systems, etc. [62].

### Comparison with Other Generation Energy Technologies

Diverse studies compare carbon emissions with other types of energy generation in order to benchmark the environmental performance of ocean energy devices. Most of these comparisons present favorable results for ocean energy in terms of CO<sub>2</sub> emissions. Figure 5 shows the comparison of the devices evaluated in the present review according to other conventional electrical generation technologies; the comparison includes wave, tidal and thermal energy converters.



**Figure 5.** CO<sub>2</sub> emissions of ocean energy technologies (OET) compared with other generation energy systems.

### 4.5. Carbon and Energy Payback Period

An important environmental criterion for evaluating the scope of acceptability of ocean energies is the energy payback period (EPB) which indicates the time period for renewable energy technology to produce the amount of energy that was used for manufacturing, maintenance, operation and the energy produced during the useful life of the system [9,53,54,59]. The EPB is obtained by dividing the total lifetime energy input by annual energy production [49]. EPB values depend mainly of annual energy production, device life, and type materials required of the manufacture stage. Additionally, another significant environmental indicator for renewable sources is carbon payback (CPB). CPB is the time period in which the CO<sub>2</sub> emissions are retrieved from renewable ocean devices. The CPB is calculated as by dividing the total embodied carbon by the annual carbon avoided by the use of the

ocean energy technologies [9,49]. Figure 6 shows the comparison of energy and carbon paybacks for the different ocean energy technologies evaluated, including: Wave, tidal and thermal energy systems. At a global scale, the WEC devices have relatively less EPB and CPB than tidal converters. Additionally, the CPB of WEC is expected to be shorter than tidal energy.

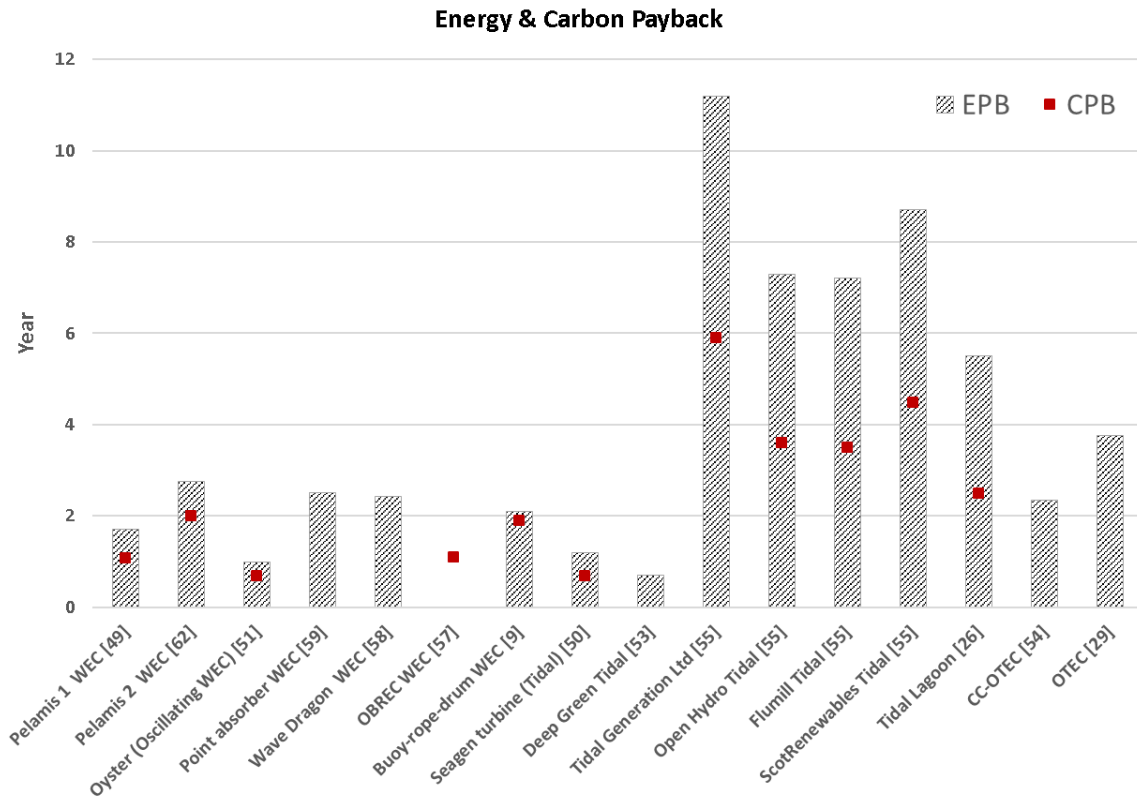


Figure 6. Energy payback period (EPB) and carbon payback (CPB) of ocean energy technologies.

### 5. Overall Discussion

Overall, the results of this analysis have shown that there is still considerable divergence in design and dimensions options for ocean energy devices which further complicates a correct comparison in terms of environmental impacts between technologies [14]. There are considerable uncertainties due to the lack of available data such as: Specific technological parameters, alternative structural components and materials as well as assumptions made in each study [9]. The environmental impacts are very much depending on size of installation and the location selected. As the uncertainty assessments of LCA results are generally extended based on assumptions and estimates, it must be noted that full statistical uncertainty is generally beyond the reach of LCAs, even for parameter uncertainty. This especially true for complex assessment targets applicable to renewable energy, and special wave ocean energy. As an example, if the age of the data is associated with an uncertainty value and the geographical representativeness with another, neither these percentage values, nor the resulting uncertainty when combining those, can be said to represent the statistical variations in results due to these factors, but the resulting value instead represents a systematically calculated quality index for the data set. Thus, uncertainty values are generally seen as quality indexes which do not predict the overall variation in results. Further, as the estimates and assumptions behind them are often based on subjective judgments, such quality indexes cannot be directly compared between studies. The renewable energy industry is today mainly focused on the life cycle inventory phase and the evaluation impact assessment phase is mainly focused on climate change impact, as this is the main focus of most stakeholders. However, other categories related to, e.g., biodiversity and marine impacts should be addressed and need to receive more attention. Parameter, scenario and model uncertainty should be evaluated both for the

life cycle inventory and the life cycle impact assessment phases. For climate change, there is broad scientific agreement related to assessment methodology. Nevertheless, for other impact categories, there is less scientific consensus, and when it comes to uncertainty, toxicity impacts can be caused by multiples substances emitted and the effects of each of them and the combinations effects is often less well-known. For example, climate change effects [77,78] are related to around 80–90% of GHG, and in any other impact category, the number of substances/flows is between one and 40. Consequently, uncertainties are higher for toxicity as of the amounts of substances cannot be studied and modeled specifically, or in great detail [79].

Though, all studies agree that the main environmental impacts of ocean energy devices from an LCA perspective are due to raw material extraction and the manufacturing stage, while installation, maintenance and operation do not show significant impacts [12]. Furthermore, as observed in Section 4.4, the OET provides a satisfactory outlook in environmental terms associated with other energy generation technologies, especially in global warming [12]. In an integrated vision, with the aim of reducing the environmental impacts of these systems, a probable alternative is that the devices can be installed in arrays or ocean energy farms in the future. This action will significantly reduce the environmental impacts produced by structural components and materials [9]. Additionally, the development and research of OET should focus on alternate materials for device manufacturing, better mooring and foundations systems, improvements in shipping operations during construction and installation of ocean energy devices (reducing the distance of shipping operations, as well as the search for more efficient fuels), and increasing the efficiency and reliability of the new device [10,12,14,59].

Another critical factor to consider is that all ocean energy devices installed at offshore locations are connected to land through power cables that emit electromagnetic fields. The magnitude of these fields vary with cable dimension and grid design [19]. All studies performed are addressed to the amount of energy generation without considering the fluctuations in storage or grid integration. In this sense, some of the main research areas in OET are electricity storage and grid integration, a comprehensive LCA, and technical and economic evaluation which are required for approval purposes [10,14,15]. In addition, another issue to be noted that we have detected in our research group is the sustainable development of coatings through LCA studies where different potential components for corrosion and biofouling protection can be evaluated. Quantification of both the environmental impacts and environmental benefits for coatings for the corrosion and biofouling protection of ocean renewable energy infrastructure can promote a better understanding of the consequences related to its use. Marine biofouling is the undesirable accumulation of plants, microorganisms, algae, plants and invertebrates on marine surfaces immersed in sea water [80,81]. It may affect marine biodiversity of the ecosystem, hydrodynamics of water flows and conflict with the efficiency of marine energy devices [82,83]. Effects on aquatic organisms can range from temporary water quality degradation (decline in dissolved oxygen content) to biotoxicity and bioaccumulation of previously buried pollutants such as heavy metals [84]. Therefore, it is important to investigate in detail the adverse effects caused by this environmental phenomenon and how it affects device performance. Antifouling coatings are one of many additives usually incorporated into a marine protective coating system as the foundation of marine energy devices. An optimal antifouling coating should be environmentally acceptable, anticorrosive, stable, durable, resistant to erosion, long life and economically viable [82,85]. Various types of antifouling coatings have been developed to control corrosion and biofouling protection of marine renewable devices [85]. Polymeric and ceramic coatings offer a promising method of protecting the foundation on the seabed by concentrating antifouling compounds around surfaces with much less environmental impact than traditional coatings and they are easy to apply at affordable cost [85–89].

Although, investments in ocean energy systems have increased considerably over the last decade and have a lower risk profile than conventional energy sources, these energies still involve considerable technological, economic, social and environmental regulatory risks, depending on the technology type and region for the deployment of devices [7,90,91]. In this context, it is of great importance to consider extensive research and understanding of the environmental implications of OET before its

real-scale application [14]. While it is true that the degree of success in extracting these types of energies depends on the long-term availability of the energy source and the adequacy of the regions chosen for the implementation of OET [92], it is crucial to evaluate these technologies from an environmental perspective, and include this data among other important factors, such as the cost of investing, geographic area, and social aspect to its overall assessment [56,92]. Therefore, the technological development in the ocean energy sector should be evaluated from a sustainable holistic approach, considering the possible social, economic and environmental impacts associated with the entire life cycle of devices used. Finally, it is worth noting that future environmental studies should also focus on general issues related to marine environments such as: Artificial reef effects, biofouling, bird migration, environmental changes and hydrodynamics effects, water quality changes and possible pollution, areas that have not been deeply studied and that could cause cumulative impacts and compromise the life of marine and coastal ecosystems [14,92]. In this regard, Felix et al. [92] mentions that mitigation strategy designed to avoid ecosystem alteration due to the use of OET is a priority in future projects.

## 6. Conclusions

Ocean energy currently represents a high potential for global power generation. During the last two decades, research and technical development of ocean energy systems has been growing and hence also the study of the possible environmental impacts and benefits related to this renewable technology. In this sense, the application of LCA methodology has provided a better knowledge in environmental terms of ocean energy systems. In this literature review paper, available information was compiled and classified based on the type of energy conversion technology used for ocean energy generation (wave, tidal and ocean thermal). The results of this review show that most of the LCA studies are focused on the life cycle carbon emissions assessment (11 of 18 published articles), as well as a comparison to other conventional and renewable energy systems. Hitherto, tidal and wave energy are currently the most advanced systems in science, development and technology. So far, good quality studies are lacking, especially for ocean thermal energy and salinity gradient technologies. Overall, the analyses show that the main environmental impacts of ocean energy devices are due to raw material extraction of structural components, manufacturing devices, energy consumption and mooring foundations. In this way, some alternatives to mitigate these impacts are as follows: Energy farm design, alternate structural materials and components, improvements in shipping operations, and increases in the efficiency and reliability of new devices. These relevant findings could help technology developers and decision and policy-makers design appropriate strategies to maximize a positive and sustainability environmental contribution. Lastly, the integration of economic and social aspects should be considered in the scope of future LCA studies in order to evaluate the implementation of new sustainable OET, including whole ocean energy arrays or ocean energy farms, as well as considering the marine environmental impacts.

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